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The northern Pennines revisited: Moor House, 1932–78

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Editorial note: This paper was submitted by Professor Manley in March 1979, and while discussion of it was going on we received the sad news of his untimely death. We are very grateful to Mrs Audrey Manley for making available to us her husband's original MS and other working papers which have enabled us to clarify certain obscurities in the copy as received. The following extracts from his covering letter will, we think, be of general interest:

The circumstances are these. There has been a development of interest of late in the climatology of our higher uplands. The Royal Meteorological Society had a meeting, largely for the younger amateurs, last October, and I was asked to open the affair with the first address. This led me to reflect a bit on the work I set going (nearly 50 years ago!) at Moor House in the northern Pennines—for long the highest place in Britain at which any observations were kept (and long before the days of enormous research grants). It got a notice in the *Meteorological Magazine* in 1932.

The Nature Conservancy took Moor House and its surroundings as a National Nature Reserve in 1952 (largely Prof. Pearsall's work) and have kept good daily observations there. The whole place has a lot of botanical interest in particular. I gave them a digest of my earlier observations (1932–47) but last year when I went up there and stayed for three days or so I reflected that this old series of observations ought to be standardized on to the later set, and so provide nearly 50 years, with the prospect indeed of further extension backward in time for the benefit of the tree-growth people and others.

But making the 'standardization' has been quite a long and tedious job. (Changes of site, instruments, hours of observation, etc. etc.). Still it has been done. One rather surprising feature emerged; the unsuspected and quite large effect of the proximity of the house on the earlier observations. It seems to me that this might well be demonstrated, for the benefit of future workers. Then there is the interesting evidence that the result of such a wide extent of undrained uncultivated wet moorland, at 1800 or more feet, is to *lower* the prevailing air temperature as measured by the usual method in a Stevenson screen. This is most probably a matter of coarse vegetation and soil conductivity (after Brunt 1941) but it raises, or could raise, quite a variety of questions on the possible effect of local environmental changes, that are not merely 'urban building' or 'pollution'.

Hence I have compiled the attached account and commentary, together with a table of monthly means over 48 years which may be of future use for people working on the area.

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There are of course lots of other meteorological elements that could be discussed, but some have only been run for a few years, in relation to other researches, and it would seem to be preferable to defer treatment until they have a longer series.

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Postscript. Northern Pennine snow cover this year is already on the way to breaking records.

The old Scottish record in the 1880s at Dalnaspidal railway station (1420 ft) on the Drumochter gave temperatures but little higher; but with less rainfall and better drainage, opportunities for cultivation were a little better.

In the following text, *m.n.* stands for marginal note by Professor Manley on his original manuscript and editorial additions are indicated by square brackets.

Summary

Two series of temperature observations at Moor House, near Crossfell, are compared with each other and with records from other similar sites to provide a homogeneous series of monthly mean temperatures from January 1931 to January 1979. The effects of topography, soil and vegetation are discussed, as is the relationship of mean temperature to snow cover. Comment is also made on the adjustment of monthly mean temperatures at Durham University Observatory to allow for changes in observing practice.

Introduction

In 1932, whilst engaged in the University of Durham, I was attracted by the northern Pennines, in particular around Crossfell, as the most extensive area of bleak, uncompromising upland that England possesses. For many it provides unusual interest, with the highest inhabited dwellings, roads and settlements, cultivated land, plantations, all close to an evident treeline with climatic stresses and extremes presenting an obvious opportunity for investigation. Late in the January of that year I set up temperature observations at Moor House, a remote shooting lodge and gamekeeper's cottage on the open, treeless and windswept moorland at 1825 ft (556 m) in extreme upper Teesdale. The normal approach (snow permitting) is by car from the village of Garrigill, six miles to the north in the valley of the South Tyne. It was then the second highest inhabited house, with its nearest neighbour four miles distant. A rain-gauge was added in 1935. A note about the station was published in the *Meteorological Magazine* (Manley 1932) and later papers reviewing the observations (Manley 1936, 1943, the latter with illustrations) appear in the *Quarterly Journal of the Royal Meteorological Society*. Further papers relevant to meteorological observation in the area are in the same journal (Manley 1942, 1945) and in *Weather* (Manley 1971). Contributions by Mr W. E. Richardson, who set up an admirable series of upland observations while teaching at Alston (10 miles north of Moor House) from 1951 to 1956, should be added (Richardson 1954, 1955, 1956a, 1956b).

From earlier descriptions it will be seen that temperatures were read from a (weekly) bimetallic Meteorological Office thermograph with the older-style taller drum, set in a Stevenson screen in the walled garth on the south-west of the house and about 25 yards distant (illustration facing p. 260 of *Q J R Meteorol Soc*, **69**, 1943). The extremes were in general checked weekly against adjacent thermometers of standard pattern. Daily maxima and minima were read from the edge of the trace and tabulated for the interval 21 h–21 h for comparison with the two nearest stations, flanking the Pennines,

that were generally acceptable: Newton Rigg (559 ft) 18 miles west-north-west and Durham (336 ft) 33 miles east by north. Both are well-exposed stations on rising ground, not subject to frost-hollow minima such as prevailed at Appleby or Houghall.

This record was terminated in March 1941, but in September 1942 I brought down the mercury-in-steel thermograph that I had been running beside the summit of Great Dun Fell at 2735 ft, three miles west of Moor House, and set it up with its bulb in the screen, now erected on top of a 6-ft wall abutting on the house. This was in order to keep the recording mechanism within the window of an adjacent porch about five yards distant. This exposure, on open treeless moorland, ensured plenty of air movement, and evidence led me to think that for the purpose of establishing the prevailing temperature the results would be adequate. It had earlier been found that the westward protection afforded by an adjacent 5-ft stone wall in the original position was desirable, not only on account of the sheep; the ground is soft, and bimetallic-thermograph readings would have been seriously affected by shaking of the screen in the frequent strong winds. The great advantage of thermographs is that an absentee university don can learn much more about the local meteorology.

When it was found that the overall decline of temperature with altitude, either from Durham or from Newton Rigg, agreed closely with that observed elsewhere, e.g. by Buchan on Ben Nevis,* this seemed an adequate reason to believe that this Moor House temperature record, after reduction, was acceptable. The mercury-in-steel thermograph was finally dismantled in April 1947; soon afterwards the house was vacated, until in 1952 the whole estate was acquired by the Nature Conservancy as an upland reserve. Daily meteorological observations at 09 GMT began in July 1952 and have been continuous since January 1953 (*Monthly Weather Report*). The Stevenson screen was set up on the open moorland about 100 yards east of the house. Subsequently, rate of rainfall, anemograph, soil temperature, evaporation, stream flow, sunshine and radiation measurements have from time to time been added and provide abundant material for discussion that can also be linked with other experimental programs. For example, in contrast to 1932 there are small experimental plantations of hardy conifers, some thriving quite fairly.

From the standpoint of temperature two series of observations thus exist, and the purpose of this paper is to provide an integration. While it was thought that the earlier location near the house would give a satisfactory result in such windswept surroundings, investigation has shown that the earlier temperatures need to be adjusted quite appreciably in order to equate them with the standard of the later series.† The older site cannot now be compared directly with the newer, as a laboratory has been built on it.

Reduction of the earlier series to the later standard

It has therefore been necessary to carry out an elaborate, protracted and troublesome comparison through the nearest available climatological stations. To the east there are overlapping records at Durham (336 ft, 33 miles east by north), Ushaw (594 ft, 30 miles east-north-east) and also at Chopwellwood (445 ft, 28 miles east-north-east) and to the west Newton Rigg (559 ft, near Penrith 18 miles west-north-west), but with serious interruptions between 1948 and 1952. There was a good upland record at Bellingham, 848 ft, 33 miles north by west, from 1908 to 1963; and beyond, at nearly the same altitude there is Eskdalemuir, 54 miles distant but with a roughly similar southerly-slope

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* *m.n.* B[uchan] adopted 1 °F/270′. [This probably refers to *Trans R Soc Edin*, **34**, 1890, p. xxii, where the value given is 1 °F/275′.]

† *m.n.* The effect of the house in presenting a barrier to radiation loss about 40 ft high and subtending about one-third of the horizon is clearly considerable.

exposure.* It has already been pointed out that Appleby, 10 miles from Moor House, was not used because, like Houghall near Durham, it lay in a noticeable frost hollow; such exposures can affect the monthly means quite markedly in individual months. It is moreover desirable to make comparisons with stations both to the west and east of the Pennine watershed; weather at Moor House responds mainly to the pattern shown by places to the west, but not exclusively; in some months easterly and north-easterly winds are dominant, and much depends on their strength.

Further tedious difficulties arose because of changes in the terminal hour of observation for the daily maxima and minima. The earlier 21 h–21 h interval was maintained at Durham until 1958. At Newton Rigg 9 h–9 h was used after 1952. At Chopwellwood, Ushaw and Bellingham 9 h–9 h observations prevailed throughout. But when one makes close comparisons of such local differences over a period, evidence of the likelihood of other changes begins to appear. Screens may have been moved a short distance; instruments (or observers) may have been replaced, apparatus may have been added within the screen, external fences may have been erected or removed, ground may have been dug, trees may have grown. It could perhaps become invidious and certainly tedious to go into detail after so long an interval; suffice it to point to my detection of unsuspected thermometer errors at Durham in the later 1920s and their elimination (Manley 1941a). Scrutiny of the *Monthly Weather Report* likewise revealed a serious discrepancy in all minima at Cockle Park over many months in the 1940s.

The overall monthly means, and the mean daily maxima and minima given by the two Moor House series for each month, have been compared throughout with the stations above-named to the second decimal place. It became evident that the differences were consistently less from 1932 to 1947 than they were from 1953 onwards; at all the stations this was demonstrated for every month.†

For effective reduction to the standards of the Nature Conservancy's 9 h observations that now prevail, all the earlier monthly means, which were Fahrenheit, should be lowered by 0·6 °F. The mean daily maxima can be accepted without change,‡ that they were unaffected is an understandable result in such a windswept area.§ But for 1932–47 the mean daily minima that were derived from the screens that were nearer to the house should be lowered by an average of 1·2 °F. The overall mean daily range, 10·8 °F on the older series, thus becomes 11·4 °F, in close agreement with that observed in the present location over 26 years.

This makes an interesting result as its magnitude was unexpected. Clearly the number of 'quiet clear radiation nights' on this upland is more effective than I was disposed to think, remembering the strong and often cutting wind that assailed the daytime visitor on so many occasions. On such quiet nights the large two-storey house to the north-east would form a considerable impediment to outgoing radiation.‖ With regard to the location of the earlier screen, this would be more likely to affect the nocturnal minima than the daytime maxima.

Nevertheless I have found the magnitude of the effect surprising, as it is of the same order as that observed in, for example, an open housing area in a modern suburb. It suggests that it is the impediment to outgoing radiation that should be considered, even in what appears to be a windy area. The effect, on minima in particular, of changes in location of the screen in regard to the hangars on a large airfield can be cited. Such moves may appear to be relatively unimportant, but they need to be taken into account when it is a question of argument with regard to slow climatological trends and their possible causes.

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* *m.n.* There is no satisfactory station to the southward.
† *m.n.* 5·06 21/21 5·68 9/9 to NR [NR = Newton Rigg].
‡ *m.n.* for practical purposes.
§ *m.n.* within the normal limits of error of good thermometers.
‖ *m.n.* subtending about one-third of the horizon and standing 35–40 ft high.

It may be asked what precautions were taken to eliminate the lag that must be expected from a bi-metallic thermograph. Extremes were checked against adjacent standard thermometers in the screen, and the ink trace was read to its outer edge. The internal impediment by the thermograph of the screen, of standard Meteorological Office pattern (about 30 × 24 × 18 inches, by recollection) might have a small but not negligible effect. It may further be asked whether the results during the last four years (1943–47) that were derived from the mercury-in-steel bulb, in the screen on the wall nearer the house, might also be suspected. I was unable to find any residual difference that could be ascribed to this change of instrument and location, sufficient to justify separate treatment. Bearing in mind the small thermometer errors that are likely to occur with Stevenson screen observations in any event, it has seemed to me reasonable to treat all the earlier monthly means alike in assembling the table (Table I).

This table is printed at length as it provides the longest upland series above 1500 ft that we have and that seems likely to continue. The conspicuously marginal climate at Moor House is of decided interest to botanists in particular. The gap May 1947–June 1952 has been filled after application of the mean differences of temperature acquired from the later records between Moor House and the several stations previously mentioned. Some weighting has been given to the resultant according to the prevailing character of the month. When unsettled westerly weather is dominant, for example, Moor House tends to follow Newton Rigg, or even Eskdalemuir, more closely than Durham. Approximations for the year 1931 have been added to round off the first decade. Average daily maxima and minima for each month since 1931 are also available, and frequency of air frost (130 days, 1956–75); average and absolute extremes can be given, but for the earlier years the quotation of extreme minima must be approximate. Extreme minima are interesting; Moor House lies on the gentle slope, within the upper Tees basin, but about 60 ft above the river, whose valley floor, at 1760 ft, is more than half a mile distant to the north-east. Hence the thermometer at the House does not record the lowest temperatures that without doubt occur in the basin. At Moor House the extreme minima are not lower than those observed under exceptional conditions in the lowland valley-bottoms such as Houghall, Haydon Bridge or Appleby.

We do not know what further considerations of the possible vicissitudes of climate on the northern Pennines will arise in future. I have therefore devoted some thought to the prospect of extension of the temperature record, as well as other elements of climate. Several earlier records of value have been kept, notably Allenheads (1360 ft) and Alston (1145 ft). At Allenheads, 10 miles north-east from Moor House, observations probably organized by Thomas Sopwith began about 1836: I have not found them before 1857. They continued till 1876, and were summarized in Glaisher's *Quarterly Returns*. Averages for 1856–95 were computed by Buchan (1898)—see also Bartholomew's 1899 Meteorological Atlas. It seems likely that a Glaisher Stand was used. Afternoon maxima on the slope were relatively favourable and night minima were not exceptionally low, the location being well up the valley side. Alston (1880–86), actually Lovelady Shield in the Nent Valley four miles distant and eight miles from Moor House, used a Stevenson screen and reported to the Royal Meteorological Society. Buchan likewise computed and published averages, and added those for Hawes Junction (1883–98) at 1135 ft, a telegraphic station for the Meteorological Office, 25 miles south of Moor House. But we have no northern upland stations to fill the gaps; a 'bridge' of sorts could be made by extrapolation from Newton Rigg and Ushaw College, Durham, West Witton and Bellingham.

I have tried out the relationship between the monthly means at Moor House and the two northern English series that I have compiled for much longer periods: 'Lancashire', representative of the lowland around Preston, since 1753 (Manley 1946) and Durham (University Observatory) since 1847 (Manley 1941a). Decadal differences are reasonably accordant and there is sufficient material to extend 'Durham' back to 1795, a task now in progress. Fluctuations of the mean temperature over the high Pennines can therefore be reasonably assessed at least from 1800 onward (see Table II). The significance of this will

Table I. *Monthly means of temperature at Moor House (1825 ft above sea level)*, 1931–79

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees Fahrenheit						
1931	30·2	30·7	31·1	37·2	44·0	47·9	51·4	50·0	45·6	40·8	38·0	34·5
1932	36·0	32·1	33·0	34·9	41·7	49·1	52·8	53·5	47·2	39·4	36·2	36·0
1933	30·7	31·4	38·6	40·2	45·6	52·1	55·4	54·5	50·1	42·4	35·0	30·3
1934	34·0	34·9	32·0	37·3	43·2	50·0	56·0	51·1	49·5	41·8	36·4	38·5
1935	33·3	33·1	36·2	37·2	41·7	50·8	54·0	54·0	46·6	40·2	36·9	30·3
1936	31·2	29·5	36·0	35·1	43·7	49·5	50·9	53·5	51·1	41·4	36·7	33·8
1937	34·0	32·0	28·1	39·9	45·9	48·9	54·0	55·0	48·1	43·5	35·7	30·4
1938	34·5	34·0	41·5	38·7	42·3	48·8	51·3	52·2	48·2	42·9	40·7	33·6
1939	30·2	35·1	35·1	39·9	45·8	50·1	52·1	53·7	49·0	39·9	39·8	31·5
1940	25·8	28·8	34·5	39·5	48·1	55·5	50·5	50·9	46·7	41·5	37·9	33·2
1941	23·8	28·6	32·7	34·3	41·1	51·2	53·3	50·8	51·5	42·7	36·8	36·4
1942	27·9	25·2	31·2	39·9	43·2	49·9	50·8	53·2	47·7	43·1	34·9	37·1
1943	32·1	36·1	37·0	41·3	43·9	49·8	52·6	51·1	47·0	43·8	35·9	33·2
1944	35·9	30·6	34·3	42·0	43·4	47·9	52·9	54·2	46·2	40·7	33·8	32·5
1945	25·4	36·7	39·1	41·0	44·7	49·1	55·4	51·8	49·3	47·4	39·9	34·5
1946	30·3	33·8	34·1	41·7	42·4	47·1	52·2	50·0	48·6	41·5	40·8	31·4
1947	29·4	22·0	27·8	37·1	47·0	51·8	54·0	57·0	50·0	45·0	36·5	34·3
1948	32·1	33·0	39·8	40·5	43·1	48·2	53·2	50·8	48·9	43·1	38·6	33·9
1949	34·5	35·0	33·4	42·6	44·9	51·0	54·2	53·5	52·8	44·8	36·5	34·4
1950	32·4	32·0	37·3	36·5	44·0	52·6	52·6	51·5	46·3	41·7	34·7	26·5
1951	30·7	30·2	30·8	35·9	40·5	47·5	53·2	50·5	49·2	43·4	39·6	34·3
1952	28·1	31·1	35·3	41·3	47·4	49·2	53·3	52·3	43·7	40·6	32·2	30·7
1953	33·5	33·3	38·5	36·6	47·5	50·7	51·6	53·0	50·3	42·7	41·1	38·1
1954	31·1	28·1	33·6	38·3	45·9	48·1	49·4	50·3	45·9	45·7	37·5	36·5
1955	30·1	24·7	29·1	41·4	40·7	47·7	55·6	55·3	50·1	41·4	39·1	35·3
1956	31·3	24·7	35·9	36·2	44·8	48·3	52·6	48·0	50·6	43·1	37·1	37·1
1957	35·1	32·1	41·4	39·3	43·5	49·7	53·4	51·7	45·9	44·5	37·7	33·9
1958	30·7	31·5	29·1	37·3	41·9	48·9	52·5	52·9	51·3	44·6	37·5	33·1
1959	27·9	35·1	37·4	40·3	47·1	50·6	53·5	54·0	49·2	47·6	38·3	36·7
1960	31·5	30·9	35·3	40·7	46·7	52·3	50·7	51·1	47·9	43·6	37·0	32·0

Table I *continued*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
						degrees Celsius							
1961	−1·2	2·6	4·3	5·3	6·5	9·6	10·3	10·4	10·4	6·7	2·9	−1·5	
1962	0·3	0·1	−2·5	3·1	5·9	8·7	9·6	9·7	8·3	6·8	1·3	−0·3	
1963	−4·1	−5·3	1·8	3·9	5·6	10·0	10·7	9·5	8·3	6·5	3·4	−0·5	
1964	0·9	0·1	−0·3	4·5	8·3	9·1	10·9	10·7	9·3	5·3	3·2	−0·9	
1965	−0·9	−0·7	0·1	3·7	6·9	10·3	9·3	10·3	8·5	7·3	−0·1	0·1	
1966	−0·6	0·1	2·3	1·5	6·7	10·9	10·5	10·1	9·9	5·8	1·8	0·7	
1967	0·5	0·9	1·9	3·5	5·2	9·3	11·3	11·3	9·3	5·9	2·3	0·5	
1968	0·3	−3·0	0·5	3·7	4·9	10·3	10·2	10·9	9·3	8·5	2·1	−0·7	
1969	1·1	−4·2	−1·9	2·3	6·2	9·5	12·0	12·3	9·4	9·4	0·4	−0·2	
1970	−0·5	−2·5	−0·9	1·3	8·3	11·3	10·5	11·9	10·1	6·3	2·9	0·9	
1971	1·2	1·2	0·9	3·4	7·0	7·5	12·3	11·1	10·2	7·3	2·3	3·4	
1972	−0·1	−0·1	2·1	3·8	6·3	7·3	10·5	10·3	7·2	6·3	1·8	1·8	
1973	0·9	−0·1	2·6	2·0	6·8	10·7	11·2	11·3	9·4	5·3	1·7	0·5	
1974	1·9	1·5	1·3	3·5	7·0	8·5	10·3	10·5	7·5	3·3	2·7	3·3	
1975	2·5	1·3	0·5	3·8	4·7	9·8	12·3	14·2	8·3	6·3	2·4	2·0	
1976	1·3	0·7	0·1	3·5	6·7	11·8	12·5	11·8	8·7	6·7	2·3	−1·6	
1977	−1·6	−0·5	2·3	2·2	5·5	8·3	11·3	10·6	8·5	7·9	1·5	0·2	
1978	−1·3	−2·5	1·9	2·1	7·5	9·1	(10·1)	(10·8)	(9·4)	(8·2)	(4·3)	(−0·5)	
1979	(−4·1)												
Means 1941–70	−0·6	−0·9	1·2	3·8	6·7	9·8	11·2	11·0	9·2	6·6	2·6	0·7	(Year) 5·1

Sources. 1931–47 from earlier observations set up by G. Manley (*Q J R Meteorol Soc* 1936 to 1943). Now standardized to the Nature Conservancy's station, 120 yards distant, 1953–78. Gaps filled by careful comparisons with other stations. Bracketed values in 1978 and 1979 are estimates based on records from Durham, Lancaster and Eskdalemuir.

Table II. *Monthly means of temperature at Durham, January* 1941– *January* 1979.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						degrees Fahrenheit							
1941	31·7	34·9	38·0	42·0	46·7	56·0	61·4	56·7	57·2	48·9	42·1	41·7	46·4
1942	33·3	31·8	38·0	45·4	49·2	56·1	58·1	59·7	54·3	50·1	41·2	41·2	46·5
1943	37·3	42·0	42·7	48·4	50·7	56·1	57·6	57·7	53·8	49·0	41·7	38·7	48·0
1944	41·7	38·0	40·9	48·0	49·8	53·7	58·7	59·7	52·6	47·2	41·3	38·0	47·5
1945	32·7	43·5	46·4	46·3	50·7	55·7	60·7	58·3	55·4	51·3	45·1	39·4	48·8
1946	36·1	41·1	40·7	48·5	48·2	54·8	60·0	56·7	54·8	47·7	45·3	37·4	47·6
1947	35·9	30·2	35·1	45·3	52·6	57·2	60·7	62·4	56·7	50·6	42·3	40·4	47·5[a]
1948	38·7	39·6	44·9	46·8	49·5	53·9	58·6	56·7	55·1	49·0	43·3	39·6	48·0
1949	40·1	40·8	40·0	48·9	50·9	57·4	61·1	60·1	58·9	51·3	42·8	40·9	49·4
1950	39·2	38·4	44·2	44·0	48·9	59·5	59·5	58·1	53·5	48·6	41·3	33·3	47·4
Mean	36·7	38·0[b]	41·1	46·4	49·7	56·0	59·6	58·6	55·2	49·4	42·6	39·1	47·7[c]
1951	36·7	36·8	37·7	42·6	46·4	54·0	59·6	57·3	55·3	48·3	46·0	39·7	46·7
1952	35·0	38·1	41·8	47·2	53·9	56·6	60·6	59·1	50·7	47·0	38·7	36·6	47·1
1953	39·3	40·1	42·0	42·7	53·2	54·5	57·7	59·6	55·9	47·5	46·2	42·7	48·5
1954	36·9	34·2	40·1	44·5	50·3	53·9	56·7	56·1	52·7	51·6	42·6	42·3	46·8
1955	35·2	32·8	36·8	47·6	46·8	53·5	61·6	61·4	55·9	47·3	44·3	39·7	46·9
1956	36·3	32·3	40·3	41·8	57·9	53·3	58·1	54·0	55·3	48·5	42·3	41·1	46·8[d]
1957	41·1	37·9	45·9	45·5	43·7	56·3	59·5	57·5	52·3	49·6	43·7	39·3	47·7[e]
1958	35·9	37·9	36·3	44·0	48·7	53·6	58·3	58·7	56·8	49·5	41·9	39·2	46·7
1959	33·3	39·0	43·7	47·0	52·3	57·3	61·1	61·7	56·5	52·8	43·3	40·7	49·1
1960	37·7	37·1	40·8	47·1	52·1	55·7	57·5	57·1	54·3	49·2	42·2	38·1	47·4[f]
Mean	36·7	36·6	40·5	45·0	50·5	54·9[g]	59·1	58·3	54·6	49·1	43·1	39·9	47·4
						degrees Celsius							
1961	3·9	5·9	8·1	8·3	9·8	12·9	13·9	14·4	14·0	9·7	5·3	1·1	8·9
1962	3·8	4·3	1·9	7·0	9·6	12·5	13·2	13·3	11·8	9·9	4·6	1·3	7·8
1963	−0·5	−1·2	4·7	7·9	9·9	13·5	14·2	13·2	12·0	9·9	6·7	2·9	7·8
1964	3·2	3·7	3·0	8·4	12·1	12·7	14·7	14·3	13·1	8·5	6·3	2·1	8·5
1965	2·4	3·4	3·7	7·3	10·1	13·4	12·5	13·5	11·9	10·0	3·4	2·5	7·8
1966	1·5	3·3	6·2	5·1	10·3	14·3	14·1	13·5	13·3	9·1	5·3	2·7	8·2
1967	3·3	(5·0)	6·5	7·3	8·7	12·9	14·9	14·7	12·5	9·5	(5·0)	3·6	8·7
1968	(3·4)	1·3	5·9	7·2	8·1	13·5	13·2	14·3	13·1	11·6	5·5	2·5	8·3
1969	4·1	(0·2)	2·7	6·5	9·5	13·1	15·9	15·8	13·5	12·2	3·9	2·7	8·3
1970	2·1	2·1	3·6	5·9	11·6	14·9	14·6	15·7	13·7	10·1	6·1	4·3	8·7
Mean	2·7	2·8	4·6	7·1	10·0	13·4	14·1	14·3	12·9	10·1	5·2	2·6	8·3
1971	3·7	4·5	5·0	7·1	10·7	11·2	15·9	14·5	13·7	10·4	5·5	6·5	9·1
1972	3·1	3·3	5·4	8·1	9·8	11·3	14·4	14·5	11·2	9·7	5·5	4·3	8·4
1973	4·0	4·3	6·5	6·0	10·1	14·3	14·9	14·5	12·8	8·5	4·8	3·7	8·7
1974	4·7	4·8	4·7	6·1	10·4	12·3	14·0	14·1	11·1	7·2	5·7	6·6	8·5
1975	5·6	3·8	4·1	7·7	7·9	13·1	15·9	17·5	11·9	8·8	5·3	5·3	8·9
1976	4·7	4·1	4·1	7·1	10·5	15·3	16·4	15·9	12·0	9·7	4·7	1·9	8·9
1977	1·9	3·3	5·9	6·5	9·1	11·5	14·5	14·3	12·3	10·6	5·7	5·1	8·4
1978	1·9	0·9	6·3	6·1	10·7	12·7	13·8	14·2	13·3	11·4	7·7	2·5	8·5
1979	−0·5												
Means 1941–70													
°F	36·8	37·2[h]	40·7	45·4	50·0	55·7	58·7	58·2	55·0	49·5	42·4	38·5	47·3
°C	2·7	2·9	4·8	7·4	10·0	13·2	14·8	14·6	12·8	9·7	5·8	3·6	8·5

[Some of the means in the above table differ by more than 0·1 °F from those in the original MS. The original values were as follows:

(a) 47·7 (b) 38·6 (c) 47·0 (d) 46·3 (e) 48·1 (f) 47·7 (g) 55·2 (h) 37·4

Parentheses enclosing certain values occur in MS but are unexplained.]

Reference: paper by G. Manley 'The Durham Meteorological Record 1847–1940', table on pp. 370–371 of *Q J R Meteorol Soc*, **74**, 1947. This table of adopted mean monthly temperatures was completed for 1941–50 by the late E. F. Baxter. It is here completed for 1951–57 by G. Manley; and with the change in observing routine in 1958 the later values (based on 9 h–9 h daily) are added, bringing the table up to January 1979. A series of careful comparisons has demonstrated that the present-day (9 h–9 h) monthly means are so nearly the equivalent of the older 'adopted means' (21 h–21 h) that they can be used in continuation, as above. For 1847–1940 see reference above.

become evident in regard to estimation of the persistence of snow cover, and of the springtime lag in exceptionally cold seasons that can be critical for all upland production. Not only have we the capacity to make close estimates of monthly means and of rainfall since 1800 if not earlier; the monthly frequency of days with snow falling is available for some part of the Pennine area throughout.

Rain, sun, snow and frost

The area is wet and the wide extent of peat-bog and coarse moorland vegetation shows it. Rainfall has been measured since 1953, and an average of 2010 mm (79·1 inches) for 1941–70 has been computed by the Meteorological Office. A gauge closer to the house was maintained through 1935–40, and another, about ¾ mile distant, between 1876 and 1878. These indicate a similar amount. Sunshine duration is now measured, and in spite of widespread and frequent low cloud the average is more reasonable than one might expect: about 1170 hours (Eskdalemuir 1232, Durham and Newton Rigg, 1330–1350).

For some years a sunshine recorder has also been maintained on Great Dun Fell (2780 ft) on the Pennine watershed three miles to the westward; Crossfell, the highest summit, is four miles north-west of Moor House. Sunshine duration, extrapolating from the few years available, appears to average only about 850 hours, indicating how frequently the summits remain capped although the sun is shining only three miles to the east and 900 ft below.

Snow is an obvious element of interest. Frequency of fall is rather difficult to assess from the limited observations, and can be influenced by the circumstances (Manley 1978). Frequency of snow cover, however, is what most people are concerned to ask about. To the Nature Conservancy's observations I have added the close estimates that I drew up between 1932 and 1940 when I was making frequent visits and gaining experience. Between 1941 and 1952 further estimates derive from the Snow Survey data, together with daily observations by Mrs C. Tudor of Blencarn at the western foot of Crossfell of snow cover on the adjacent slopes, Mr Richardson's valuable reports from Alston, and available reports from the climatological stations at Bellingham and Ushaw. From all this, the overall annual average for 1931–79 can be put at 70 days, ranging in individual 'winter seasons' from 27 to between 110 and 115.* Precise assessment is not always easy on this wide peaty moorland, gullied here and there and subject to much drifting; a characteristic appearance during thaw is shown facing p. 260 of the *Quarterly Journal of the Royal Meteorological Society*, Vol. 69, 1943.

It becomes interesting to plot the number of days with snow cover for each month against the mean temperature. The variation is quite wide; some cold months may also be dry, some comparatively mild months may have persistent cover after a heavy fall in the preceding month. In general, however, there is an evident linear relationship between days with snow cover and mean temperature November–April. With a likelihood of 33 days at a mean of 2·5 °C the increase is to 115 days at a mean of − 0·5 °C. For the period, 70 days and 1·1 °C are the averages.

If we assume the prevailing lapse rate in our maritime climate to be 0·65 °C/100 m, the equivalent increase with altitude above Moor House in the annual number of days should be about 18 days/100 m. Hence, from an average of 70 at Moor House we might by extrapolation deduce 210 at the summit level of Ben Nevis, which agrees quite fairly with observation. But many variables are involved; for the present, however, it seems reasonable to suggest that the persistence of a general snow cover on our mountain summits is probably more closely related to the mean temperature than to the frequency of occurrence of days with snow falling. There is, however, a broad relationship between the number

* *m.n.* 121 in 1978–79.

of days with snow observed to fall at Eskdalemuir, where the standards are those of a first-class Observatory, and the number on which snow lying is observed 1000 ft above at Moor House.

Following an earlier argument (Manley 1949) it would be reasonable to extrapolate from the Moor House observations and suggest that under present climatic conditions small glaciers might be found in the northern Pennines if they attained a little over 1800 m or 6000 ft with a mean annual temperature $-$ 3 °C or a little lower.

With regard to days with 'air frost' (screen < 0 °C), between 1956 and 1975 the annual average is 130. The earlier series of observations, closer to the house, gave 113, sufficiently in agreement allowing for the less open exposure. Air frost has been recorded in every month. Ground frost totals (1957–65) are much higher than those for air frost, an interesting point having regard to the coarse vegetation and lack of drainage. There is some reason to think that the air temperature over this wider stretch of uncultivated and undrained upland is on the whole lower than if the area were reclaimed.

Local consequences of an exceptional upland environment

The mean temperature of the air at Moor House, as derived from the daily maxima and minima read at 9 h in the Nature Conservancy's screen, is 5·1 °C for the period 1941–70. If we extrapolate from the surrounding lowland stations that keep 9 h observations in similar screens, and use the commonly accepted lapse rate for maritime temperate climates such as ours, 0·65 °C/100 m (or 1 °F/280 ft) we shall find that at the level of Moor House an annual mean of approximately 5·4 °C might be expected. This implies that the surface air at screen level at Moor House is for one reason or another cooler than we should expect at that altitude. The argument, however, depends on the extent to which one can accept mean temperatures drawn up on that basis as being strictly comparable.

It is well known that over a decade or more the mean temperature in a well-defined frost hollow, such as Rickmansworth in the past, can be as much as 1 °C below that shown by stations at similar altitude nearby.* Moor House, however, does not occupy a frost hollow; it is on the gentle slope of the broad upland basin of the Tees, about 60 ft above the river which is over half a mile distant. If we were able to tabulate the hourly readings from a continuous record we should know better by how much the mean of the sum of such readings differed from $\frac{1}{2}$(max. + min.). In general it is lower, but not by the same amount at all types of station, especially if there are buildings in the neighbourhood. We might certainly expect that it would be lower in an upland locality where incoming daytime radiation is more intense, but outgoing radiation towards and after sunset is more rapid.

We must further take into account the nature of the surface soil and vegetation. At Moor House the coarse vegetation of the undrained uncultivated moorland, with many irregular peat bogs and incipient gullies predominates over a great distance. The effect of such coarse vegetation with its matted roots was long ago noticed by Brunt (1945)[?], as the area on which, around an airfield, ground mist would first become visible in the cold surface air soon after sunset on clear calm radiation evenings after showery weather, pointing to the stagnation of a layer adjacent to the ground among the coarser grasses. It has already been noted that the frequency of ground frost at Moor House, compared with air frost, is high.

On balance, it is a justifiable conclusion that this widespread uncultivated undrained vegetation cover provides a reason why the average temperature is lower than we might fairly expect compared with the lowlands. No doubt the lowering of both day and night temperatures when there is a persistent snow cover helps, but this will not on the average operate on more than one-fifth of the days and not all those will provide clear skies and quiet air. Moreover, in extremely cold anticylconic weather with a lowland snow cover as well, the minima in the lowland valleys are as low as, or lower than, at Moor House;

* *m.n.* Hawke, *Q J R Meteorol Soc*, **70**, 1944.

here we need to recall that Moor House itself does not lie in the bottom of the wide upland Tees basin. A more detailed consideration of the daily rise and fall of temperature on such a moorland would appear likely to prove rewarding, together with the maintenance, in particular, of some observations in the flats beside the upper Tees, at about 1760 ft near the main gate of the reserve.

Light might indeed be thrown on the possible changes in the local range of temperature at such a station as Eskdalemuir in the Southern Uplands of Scotland. These uplands have long been known for their very great extent of the pale, coarse mat-grass (*Nardus stricta*) which has been ascribed to regression after centuries of sheep-grazing. Anyone who has paid much attention to incidence of frost and recorded minimum temperatures cannot fail to observe how remarkably low have been many of the past extremes in the Border counties, using the Stevenson screen of the Scottish Meteorological Society, at places such as Kelso, Thirlestane and Stobo Castles, Carnwath, West Linton or Drumlanrig. Above Eskdalemuir in particular there is now a very great acreage of forestry, the consequences of which will be interesting twenty years hence.

The suggestion that if Britain were an uncultivated wilderness it might be colder, to which the Moor House record appears to point, may deserve further consideration. Nothing has been said about the mean daily range of temperature; it is less than at the lowland stations, a result attributable to greater average wind speed, more cloud and less sunshine. The daily range, however, is considerably greater, here in extreme upper Teesdale, than on the summits, as shown by observations on Great Dun Fell nearby, and on other summits such as Fountains Fell (2160 ft) or Lowther Hill (2377 ft). At Moor House the extremes on record to date are 80° and − 3 °F (26·7 °C and − 19·4 °C) but the minimum of − 2 °F in 1947 nearer the house probably implied − 4° or − 5° in the more open exposure now used. There is much that could be added with regard to the several other elements now being measured, but these may well be left to future reviews.

Addendum

As a by-product of the above investigation, a useful note can be added on the adjustment of the monthly mean temperatures from the long-standing University Observatory at Durham, a site in operation since 1842, free as yet from any urban development. These, as published in the *Monthly Weather Report* (MWR), were derived from 21 h daily extremes until 1957. Because of several changes that had to be accounted for in the earlier record (Manley 1941a) I then derived a series of 'adopted means' for the years 1847–1940, based on a combination of the daily extremes with the 9 h and 21 h fixed-hour readings, a device sometimes used by the Victorians. Fixed-hour means at Durham continued to be published in the MWR for 9 h and 21 h and I have thus been able to continue the 'adopted means', until in 1958 publication ceased. Monthly means based on 9 h daily extremes must now be used, and these should be expected to differ slightly from those derived from 21 h daily extremes. However, close comparison with the other available records indicates that the means as now derived from the 9 h extremes at Durham are so close to the equivalent of any older 'adopted means' that they can be treated as a continuous series; this is a fortunate advantage for climatological discussion since Durham has provided one of our longest British records in one place to have been standardized.

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Probability forecasts of clear-air turbulence based on numerical model output

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Summary

During the 1976 Turbulence Survey, pilots' reports of clear-air turbulence (CAT) from about 4500 flights over the North Atlantic and north-west Europe were collected, the main aim being to assess the potential, as predictors of CAT, of various synoptic-scale meteorological indices computed by the operational 10-level model. An earlier assessment of the performance of more conventional, mainly subjective, forecasts of CAT prepared by the Central Forecasting Office (Bracknell) during the Survey, had shown that the probability (per unit distance flown) of encountering moderate or severe CAT within regions forecast to be particularly prone to CAT was only about double the probability of encounter outside these regions. Analysis of the pilots' reports of CAT versus various meteorological indices computed by the 10-level model (rectangle area) indicates that an index combining the predictive abilities of vertical and horizontal wind shear can significantly out-perform conventional CAT forecasts. In addition it is thought that forecasts of CAT must be stated in terms of *probability* (e.g. per 100 km of flight) if they are to convey the maximum possible information to the user.

1. Introduction

Reliable operational forecasts of clear-air turbulence (CAT) remain notoriously elusive and little advance has been made in this area of aviation forecasting over the last ten years or so. On forecast significant-weather charts prepared by the Meteorological Office, areas which are predicted to be particularly prone to moderate or severe clear-air turbulence are delineated by the human forecaster following reference to forecast upper-air wind fields, recent aircraft reports of CAT, etc. These CAT forecasts inevitably contain a substantial subjective element, and the relatively large number of synoptic features which, over the years, have been suspected to have some association with CAT, has tended to confuse rather than help the forecaster in his attempts to highlight the likely CAT-prone areas of the chart. In addition, these areas are often so broad (and contain no information on the probability of encounter with CAT) as to diminish a pilot's awareness during flight through these areas.

The intermittent or patchy nature of CAT, both in space and time, militates against the usefulness of this type of yes/no forecast, and in favour of some form of objective probability forecast based on the output of operational numerical models such as the 10-level model (Burridge and Gadd 1977) currently employed by the Meteorological Office. With this aim in mind, a survey of turbulence over and near the British Isles on several days in the spring of 1972 was mounted. Sparks *et al.* (1977) have reported the results of that survey and their main conclusions were:

(a) that CAT forecasts should be stated in probability terms if they are to convey the maximum possible information to the recipient, and

(b) that a further survey should be mounted involving a much wider range of synoptic situations in order to establish more firmly and confidently the reliability of any resulting proposed system of objective CAT-forecasting.

Although promising and potentially useful relationships were identified between some 10-level model meteorological indices and turbulence, the relatively small and biased sample of observations gathered during the 1972 survey placed an appreciable limitation on the representativeness of the results.

A further much more extensive survey was therefore mounted in 1976, the main aim being to develop a scheme for objectively deriving forecast probabilities (per unit distance of flight) of encountering

moderate or severe CAT. The main results of the 1976 survey and subsequent analysis are reported in this article.

2. The 1976 Turbulence Survey

An extensive Turbulence Survey organized by the Meteorological Office was carried out during the spring of 1976, with the co-operation of the meteorological services and airlines of Austria, Belgium, Denmark, Federal Republic of Germany, France, Republic of Ireland, Italy, Netherlands, Norway, Spain, Sweden, Switzerland and the USA. On ten pre-selected reporting days (9, 12, 15, 18, 21, 24, 27, 30 March and 2, 5 April), spaced at regular 3-day intervals during spring 1976, pilots were issued with specially printed maps covering the North Atlantic (Figure A1 in Appendix) or similar maps covering north-western Europe, and asked to record on them complete turbulence histories of their flights (cruise phase only). Information about the Survey and an example of the type of report required were printed on the back of each (Figure A2 in Appendix).

Pilots' responses were good; a total of 4378 usable maps were received (3·9 million kilometres of flight)—3805 'EUROPEAN' (2·1 million km) and 573 'ATLANTIC' (1·8 million km). Digitizing and quality control (Dutton 1980) of the reports proved a lengthy task. The quality-controlled data have been stored on magnetic tape for analysis; this has included comparison of pilots' (mainly subjective) reports with forecasts of synoptic-scale meteorological indices produced by the operational 10-level numerical model. Some basic statistics of the reports themselves are shown in Tables A1, A2 and A3 of the Appendix to this article; overall, 0·013 per cent of flight distance was reported as severely turbulent (only 8 reports in all), 1·26 per cent as at least moderately turbulent while 9·92 per cent of distance was flown in at least light turbulence. These figures relate specifically to turbulence *in clear air*.

It was also intended to include in this project an assessment of conventional forecasts of CAT, prepared in the Central Forecasting Office (CFO), and issued to aircrew at Heathrow during the 1976 Survey. The results of that assessment have already been reported in detail (Dutton 1979) and are summarized in this article; examples of the distribution of CAT reports in relation to large-scale synoptic features were also presented by Dutton (1979).

3. The data for analysis

3.1 *The synoptic-scale meteorological indices*

Output from the operational 10-level model (rectangle area, covering the North Atlantic and most of Europe) was used to compute fields of several meteorological indices believed to have some association with the occurrence of CAT. The indices initially selected for testing as predictors of CAT were wind speed (V), horizontal wind shear (S_H), vertical wind shear (S_V), vertical velocity (w), horizontal gradient of vertical velocity (∇w), vorticity (ζ_a), deformation (D); in addition it was thought that some representation of the rate of change (following the flow) of Richardson number (Ri) should be included. Following the work of Roach (1970) and Oard (1974) on this particular theme, for the purposes of this analysis the rate of change of (Ri) is split into two distinct components, one relating to the rate of change of stability (which we will call ϕ_1), and another relating to the rate of change of the wind shear term (which we will call ϕ_2); both ϕ_1 and ϕ_2 have been included for testing as CAT-predictors. Finally, an index suggested by Dixon (1976), also related to the Lagrangian rate of change of Richardson number, is included for testing (denoted as I_D).

All these (11) indices, with definitions in terms of the basic variables computed by the 10-level model, are listed in the Appendix (Table A4).

The constraints of the 10-level model dictate that the smallest volumes for which a forecast index can

be calculated are one grid-length square (100 km × 100 km) and 100 mb thick. The forecast fields used were those for verification times 06 GMT (18 h forecast based on data time 12 GMT the previous day), 12 GMT (12 h forecast based on data time 00 GMT) and 18 GMT (18 h forecast based on data time 00 GMT) on each of the ten reporting days; the period of validity of each forecast was assumed to be 2 hours either side of the verifying time (that is 04–08, 10–14 and 16–20 GMT respectively).

3.2 *The CAT forecasts prepared at CFO, Bracknell*

For each of the ten reporting days the CAT forecasts included in the 'EUMED' (covering north-west Europe and the western Mediterranean) and 'N ATLANTIC' forecast significant-weather charts for verification times 06, 12 and 18 GMT were digitized on a grid-square (100 km × 100 km) basis (the grid squares corresponding to those of the fine-mesh area of the 10-level model) by assigning, as appropriate, forecast categories 'MODERATE CAT' or 'MODERATE OCCASIONALLY SEVERE CAT' to each grid square or level lying within regions forecast to contain turbulence. All other grid squares or levels were, by default, assigned 'NIL CAT'. Incidentally, although throughout this article the 'NIL CAT' forecast category is used as the default category, it is never the intention to imply that areas outside those designated as being particularly prone to CAT will be entirely free from CAT. The 'EUMED' chart was used for areas east of 10°W, while the 'N ATLANTIC' chart was used for areas west of 10°W.

3.3 *The pilots' reports*

In the digitizing of the pilots' reports, the CAT history of each flight was divided into 'elementary' observations, one for each grid square traversed; each elementary observation included the grid square (10-level model fine-mesh area), height, time, length of track within that grid square, and highest intensity of CAT within that grid square. This format allowed easy comparison of pilots' reported CAT experiences with computed 10-level model indices.

4. Results

4.1 *Relationship between pilots' reports from the same unit region*

We will look first at the degree of correlation between pairs of reports from the same unit region ($xyzt$). When more than two pilots reported from the same region, pairs of reports were selected randomly and compared one with another; each report was used only once (a region containing only three reports would, for example, yield just one pair). Table I presents the results of such an analysis for a unit region size of 100 km × 100 km × z × 1 h for two values of z, 1000 ft and 100 mb, the latter value being the separation between standard levels in the operational 10-level model.

Table I. *Percentage probability of an aircraft encountering moderate or severe CAT as a function of the CAT experience of another aircraft flying in the same* 100 *km* × 100 *km* × *z* × 1 *h region* (1976 *Turbulence Survey*).

Vertical dimension of region (z)		Report of other aircraft in same unit region: NIL	LIGHT	MOD or SEV	ANY (background probability)
1000 ft		1·24%	5·15%	23·13%	2·16%
	R_M	(0·57)	(2·39)	(10·71)	
100 mb		1·38%	4·18%	13·81%	1·94%
	R_M	(0·71)	(2·15)	(7·11)	

This table gives the probability of encountering moderate or severe CAT as a function of the CAT experience of another aircraft flying in the same unit region, and clearly shows that, for this size of unit region, turbulence reports from different pilots are associated sufficiently closely for a report from one pilot to be a useful guide to the turbulence to expected by another pilot. It is convenient at this point (in reference to Table I) to introduce a simple measure of the usefulness of the association between one pilot's report and another pilot's experience. In the absence of any information (such as a pilot's report or the value of some meteorological index) which is specific to a small region of the atmosphere, the only estimate that can be made of the probability that a pilot will encounter CAT in that region is the frequency with which CAT was reported within regions of the same size in the whole data set. We will call this frequency (expressed as a percentage) the background frequency. For regions with horizontal dimensions of 100 km × 100 km the background frequency for moderate or severe CAT varied from 1·6 to 2·2 per cent depending on how the data subset was selected; the background frequency for all CAT (light, moderate or severe) ranged from 11·6 to 13·4 per cent. A pilot's report (or a meteorological index) must be considered useful if it can provide an estimate of the conditional probability of encountering CAT which is significantly different from this background frequency. The ratio of this conditional probability to the background frequency can be used as a measure of the usefulness of the report (or index); the ratio is denoted by R_B when it is calculated for all CAT (light, moderate or severe), and by R_M when it is calculated for moderate or severe CAT.

Referring back to Table I, the relevant values of R_M have been entered in parentheses; it can be seen that, for $z = 1000$ ft, if the first pilot of a pair reports nil CAT, then the probability that the second aircraft (in the same unit region) will experience moderate or severe CAT is just over half ($R_M = 0{\cdot}57 = 1{\cdot}24 \div 2{\cdot}16$) the background probability of moderate or severe CAT. If, however, the first aircraft reports moderate or severe CAT, then the probability that the second aircraft will experience moderate or severe CAT is more than ten times ($R_M = 10{\cdot}71$) the background probability. The figures for $z = 100$ mb (about 5000 ft at normal cruise flight-levels) show that a report from another pilot within the same unit region is still a useful indicator of the probability of moderate or severe CAT within that region. These figures also illustrate well the inherent patchiness or intermittency of CAT, in that, even when one aircraft has reported moderate CAT, the chance of another aircraft (flying at the same flight level, within the same 100 km × 100 km grid square, and passing through that grid square within one hour of the first aircraft) experiencing moderate turbulence is no higher than 23 per cent, or about one chance in four.

An investigation of the usefulness of a pilot's report for time separations greater than one hour confirmed the findings of Sparks *et al.* (1977) in their analysis of the 1972 Survey data. In particular, for a 100 km × 100 km × 100 mb volume, the ratio R_M for the case when the first aircraft reported moderate or severe CAT decreased to about 2 for mean separation time between reports of 3 hours (the value for pairs of reports within the same hour was 7·11—see Table I). This result demonstrates how quickly a pilot's report of CAT for a particular location tends to diminish in usefulness as a predictor of CAT at that location.

4.2 *Performance of conventional forecasts prepared at CFO, Bracknell*

The CFO CAT forecasts ('EUMED' and 'N ATLANTIC' forecast significant-weather charts) for verification times 06, 12 and 18 GMT were compared with pilots' reported experiences within the time periods 0300–0859, 0900–1459 and 1500–2059 GMT respectively, for each of the ten reporting days; a total of 30 'EUMED' and 30 'N ATLANTIC' forecasts were therefore assessed. The results of this comparison are summarized in Table II. Note that, in this contingency table, 'MODERATE CAT' and 'MODERATE OCCASIONALLY SEVERE CAT' forecast categories are combined into a single

Table II. *Elementary observations of CAT: CFO forecasts versus reported CAT for all flights* (1976 *Turbulence Survey*).

Pilot's experience		Category of forecast CAT NIL	MOD or MOD–SEV	ALL
Nil or light		39 630 98·62%	10 317 97·17%	49 947 98·32%
Moderate or severe		555 1·38%	300 2·83%	855 1·68%
	R_M	(0·82)	(1·68)	
All		40 185	10 617	50 802

category ('MOD or MOD–SEV'), while the pilot-report categories are reduced to 'Nil or Light' and 'Moderate or Severe'.

The numbers of elementary observations falling into each combination of forecast CAT and pilot-experience categories are given, and the percentages here approximate to the percentage probabilities of encountering CAT per traversed grid square. The values of R_M are given in parentheses. One interesting although not particularly surprising fact that emerges is that 65 per cent (555 out of 855) of encounters with moderate or severe CAT occur within regions not forecast to be particularly prone to CAT (i.e. 'NIL CAT' regions). But the most important result is that the probability of encountering moderate or severe CAT within 'MODERATE CAT' or 'MODERATE OCCASIONALLY SEVERE CAT' forecast regions (2·83 per cent per grid square, $R_M = 1·68$) is about double that within 'NIL CAT' regions (1·38 per cent per grid square, $R_M = 0·82$).

Statistical tests indicate that the apparent degree of skill, albeit rather low, in forecasting areas of CAT (moderate and severe) or NIL CAT is highly significant for both Atlantic and European flights. However, it should be pointed out that strict validity of such tests is conditional on the assumptions of random sampling and normal distribution of the variables. The data presented here satisfy neither condition since:

(a) The definition of the 'elementary' grid-square observations often results in the same (continuous) patch of CAT being counted as two or more 'elementary' observations, one for each grid square traversed within the patch.

(b) Areas of forecast CAT occupy specific synoptic-scale regions; 100 km × 100 km grid-square categories of forecast CAT therefore obviously exhibit considerable spatial coherence, so that the categories for adjacent grid squares are significantly correlated. This argument also applies, although to a lesser extent, to the actual reports of CAT, since turbulent patches often occur in conglomerates that have synoptic scale.

A more complete account of the performance of CFO CAT forecasts is given by Dutton (1979).

4.3 *Performance of individual meteorological indices as predictors of CAT*

The performance of each of the eleven synoptic-scale meteorological indices (described in section 3·1) as predictors of CAT was tested by comparing forecast values of the indices for verification times 06, 12 and 18 GMT with aircraft reports within the time periods 04–08, 10–14 and 16–20 GMT respectively. It was decided to divide the 10-day data set into two groups, a 'development' data set (6 days selected randomly) and an 'independent' data set (the remaining 4 days), the intention being to use only the 6-day data set to develop useful relationships between the CAT reports and an empirical combination of the most promising indices (through multiple regression analysis), and then to test the skill of these relationships on the independent data. The 6 days comprising the development data set were 9, 12, 18, 27, 30 March and 5 April, and this data set was used to test the skill of each of the eleven indices

individually. The relationships between reported CAT and a selection of the indices are depicted graphically in Figures 1–7. This type of graphical presentation is the same as that used by Sparks *et al.* (1977) in their report of the 1972 Survey.

The association between horizontal wind shear (S_H) and reported CAT (Figure 1) is obviously of some value. We will recall that R_M is the ratio of the frequency of moderate or severe CAT to the background frequency of moderate or severe CAT, while R_B is a similar ratio calculated for *any* CAT (light, moderate or severe). For data used in Figures 1–7 the background frequency of moderate or severe CAT is 1·68 per cent; for light, moderate or severe CAT it is 12·45 per cent. Figure 1 reveals that, in general, low values of S_H are associated with below average frequency of CAT ($R_M < 1$) while relatively high values of S_H are associated with above average frequency of CAT ($R_M > 1$). For example, for those cases with $S_H < -2{\cdot}5 \times 10^{-5}\,s^{-1}$, constituting about 18 per cent of all cases, $R_M = 0{\cdot}19$ and $R_B = 0{\cdot}51$.

Vertical wind shear (Figure 2) also shows an obvious and promising association with CAT. The probability of encounter with moderate or severe CAT increases as S_V increases. For $S_V > 7 \times 10^{-3}\,s^{-1}$ (or 7 m s^{-1} per km), the probability of encounter with moderate CAT is about three times the background frequency.

Considering that Richardson number (*Ri*), represented in Figure 3 as ln(*Ri*), is closely associated with vertical wind shear, its degree of association with CAT is a little disappointing. For values of ln(*Ri*) in excess of 1·5 the trend of R_M (decreasing with increasing (*Ri*)) is as expected, but lower values of ln(*Ri*) (< 1·5) show no significant association with the occurrence of CAT.

In Figure 4 the evident lack of any useful relationship between wind speed and CAT may at first sight appear surprising and disappointing but confirms, in association with Figures 1 and 2, that within or near jet streams the local vertical and horizontal gradients of wind assume greater importance (than the wind speed alone) in the well-documented association between jet streams and CAT.

Figure 5 shows that the association between absolute vorticity and CAT is not good. The index may, however, prove useful in identifying regions of *below* average occurrence of CAT.

The association of deformation (Figure 6) and Dixon's index (Figure 7) with CAT is similar to that for vorticity, their main value apparently being in isolating regions of below average CAT probability.

The remaining four indices (w, $|\nabla w|$, ϕ_1 and ϕ_2) exhibited no significant association with CAT and the graphs for these indices have been omitted.

4.4 *Multiple regression analysis*

Multiple linear regression analyses have been used to identify the combination of indices which exhibits the 'best' linear relationship with reported CAT. It was therefore necessary to assign numerical values to reported turbulence intensities, and a simple scale was adopted as follows: NIL = 0, LIGHT = 1, MODERATE = 2, SEVERE = 3. As they stand, many of the indices have relationships with turbulence that are obviously non-linear, and some experimentation with simple modification of some indices (for example, the replacement of S_V by $S_V{}^2$) was tried.

The regression program (University of California, Los Angeles 1977) computes multiple linear regression in a stepwise manner, entering the independent variable (index) that best helps to predict the dependent variable (CAT) into the regression equation at each step. The program continues to enter variables until the prediction of the dependent variable does not improve significantly (the level of statistical significance can be selected by the user).

The matrix of correlation coefficients between the unmodified indices is shown in Table III. Correlations with magnitudes greater than 0·3 are in bold type to highlight strongly correlated pairs such as horizontal wind shear and vorticity.

Table III. *Correlation matrix for the eleven indices (development data set).*

Variable	V	$\lvert w \rvert$	$\lvert \nabla w \rvert$	D	ζ_a	S_H	S_V	ϕ_1	ϕ_2	I_D	ln (Ri)
V	1·000										
$\lvert w \rvert$	0·217	1·000									
$\lvert \nabla w \rvert$	0·155	**0·319**	1·000								
D	− 0·026	0·076	0·202	1·000							
ζ_a	− 0·085	− 0·080	− 0·140	0·269	1·000						
S_H	− 0·134	− 0·070	− 0·112	0·196	**0·784**	1·000					
S_V	**0·386**	0·124	0·114	0·065	0·102	0·215	1·000				
ϕ_1	− 0·023	− 0·022	0·019	− 0·058	− 0·013	0·010	0·075	1·000			
ϕ_2	− 0·001	0·009	0·046	− 0·031	− 0·031	− 0·020	− 0·057	0·031	1·000		
I_D	− 0·017	− 0·068	− 0·139	0·167	**0·916**	**0·679**	0·145	− 0·028	− 0·031	1·000	
ln (Ri)	− 0·204	− 0·236	− 0·270	− 0·067	0·172	0·050	− **0·654**	− 0·057	0·035	0·184	1·000

(number of observations = 20 176)

The following empirical index (E) has emerged as the 'best' predictor of CAT:

$$E = 1{\cdot}25S_H + 0{\cdot}25S_V^2 + 10{\cdot}5$$

(where units of S_H and S_V are as in Figure 1 and Figure 2 respectively). The performances of this index on the development data set and, more important, on the independent data set, are shown in Figures 8 and 9; this graphical presentation is the same as that used in Figures 1–7, except that the results for light, moderate and severe turbulence grouped together (R_B) are not included. For comparison the performance of conventional CFO forecasts (categorized as 'NIL' 'MOD') is superimposed (pecked line); this represents the performance of conventional forecasts over the entire 10 days, the figures for which were presented in Table II (section 4.2).

Attempts to improve on the regression equation by the inclusion of topography (as held in the numerical model) have proved disappointing; no significant improvement in the skill of the CAT index was evident.

5. Discussion

In the report of the 1972 Turbulence Survey, one of the more tentative conclusions was that forecasts produced by the 10-level model contain information which allows positive predictions of CAT which are about as good as those based only on a recent pilot's report. The results of the 1976 Survey have served to confirm this general conclusion. The 1976 data set was about ten times the size of that achieved in 1972, a much larger area being covered (North Atlantic and north-west Europe) and a much greater variety of synoptic situations being sampled; any conclusions arising from the 1976 Survey must therefore carry a lot more weight than those from the 1972 Survey.

One of the main problems in the interpretation of the results is that the usual statistical tests cannot be reliably applied since they assume random sampling of normally distributed variables. The data used obviously do not satisfy this requirement, owing largely to the considerable spatial coherence exhibited by the variables. However, the 'best' empirical index, derived through regression analysis on the 1976 development data, has been demonstrated to show similarly promising skill when applied to the independent (4-day) data set (see Figure 9); that result is encouraging. The performance of CFO forecasts is relatively poor by comparison. In particular, objective forecasts based on E, the empirical index, can highlight *small* areas (about 3 per cent of total chart area, on average) of relatively *high* CAT probability (3 to 4 times the background probability), and also have the ability to isolate regions of airspace (about 10–20 per cent of total chart area) with relatively *low* CAT-probability ($\frac{1}{3}$ to $\frac{1}{2}$ the

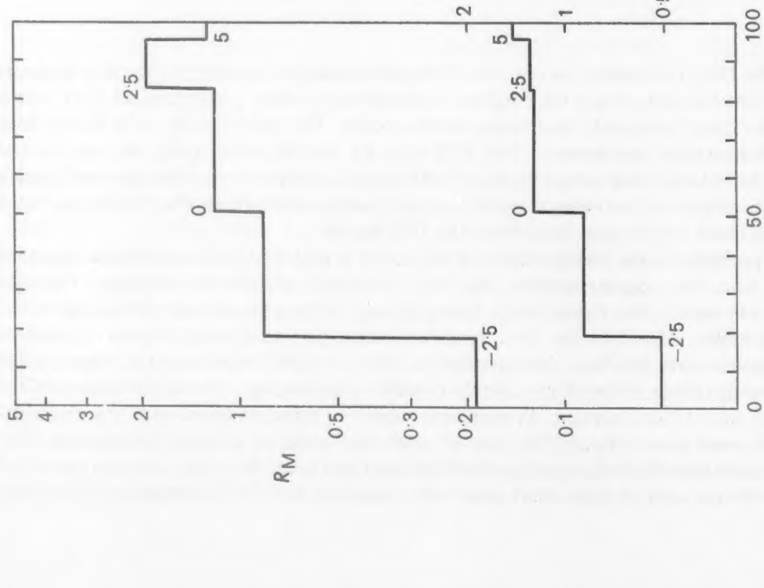

Figure 1. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of horizontal wind shear less than or equal to the values shown on the curve. Units of horizontal wind shear are $s^{-1} \times 10^{-5}$ (or m s^{-1} per 100 km).

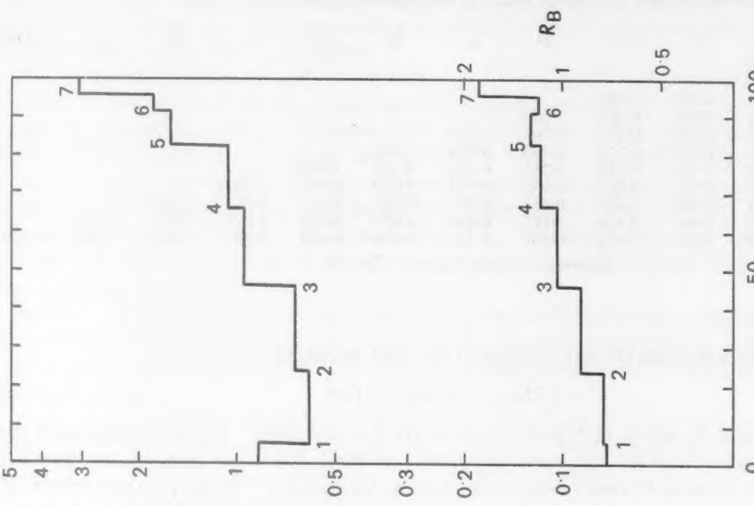

Figure 2. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of vertical wind shear less than or equal to the values shown on the curve. Units of vertical wind shear are $s^{-1} \times 10^{-3}$ (or m s^{-1} per km).

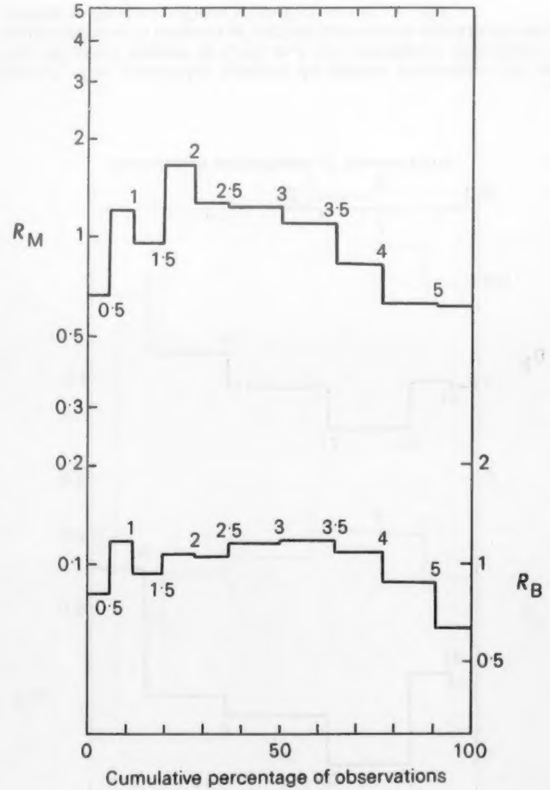

Figure 3. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of ln *Ri* less than or equal to the values shown on the curve.

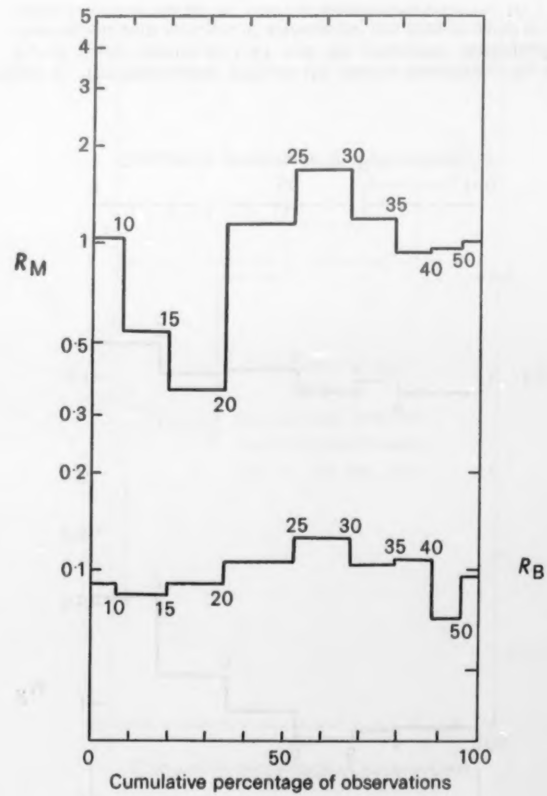

Figure 4. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of wind speed less than or equal to the values shown on the curve. Units of wind speed are m s^{-1}.

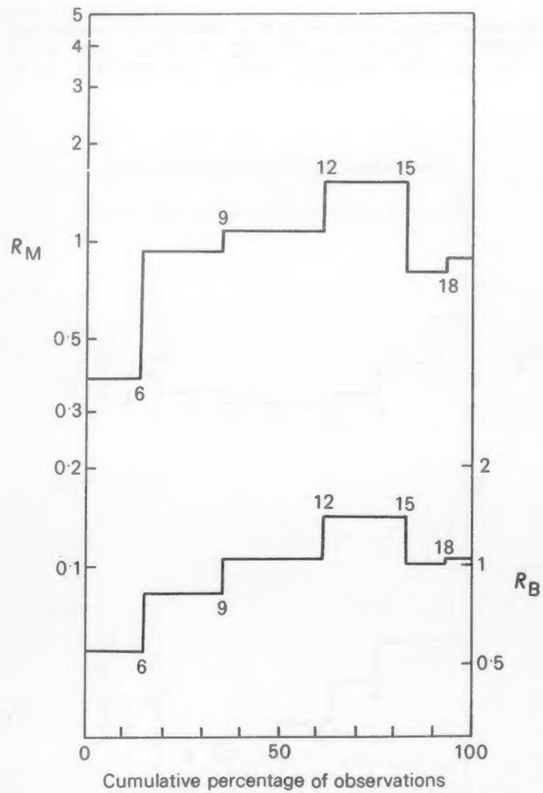

Figure 5. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of vorticity less than or equal to the values shown on the curve. Units of vorticity are $s^{-1} \times 10^{-5}$.

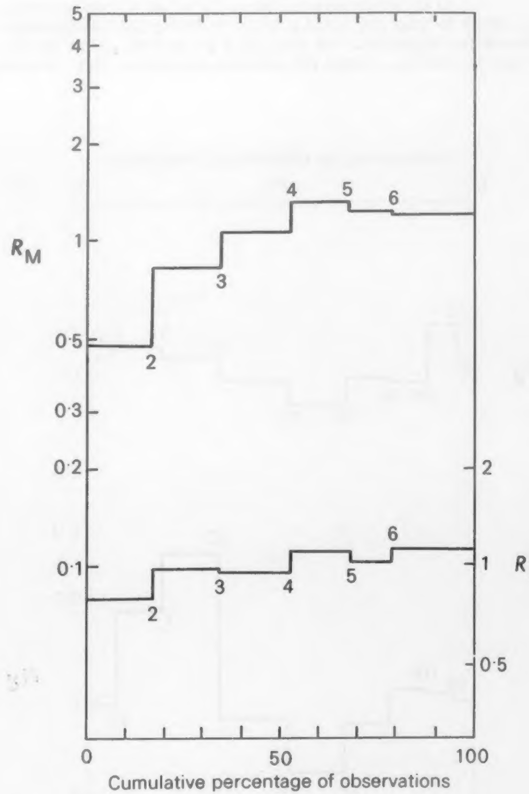

Figure 6. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of deformation less than or equal to the values shown on the curve. Units of deformation are $s^{-1} \times 10^{-5}$.

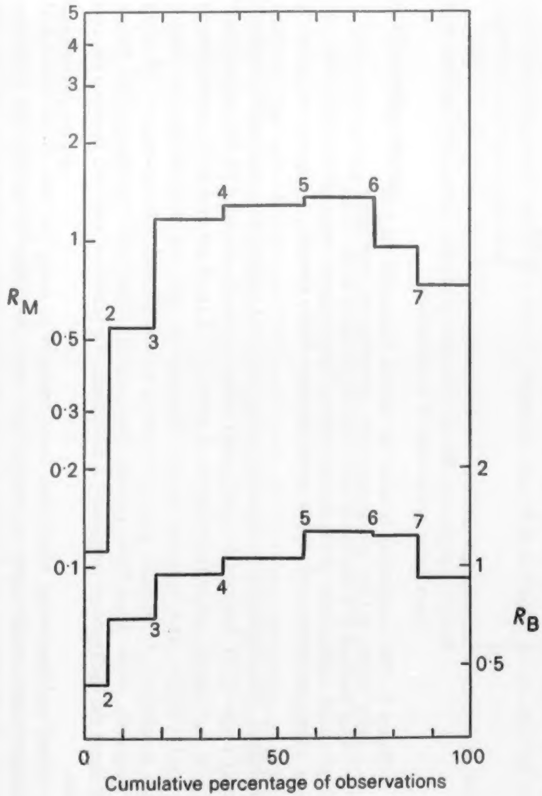

Figure 7. The relationship between the relative frequencies (R_M and R_B) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of Dixon's index less than or equal to the values shown on the curve. Units of Dixon's index are $s^{-2} \times 10^{-8}$.

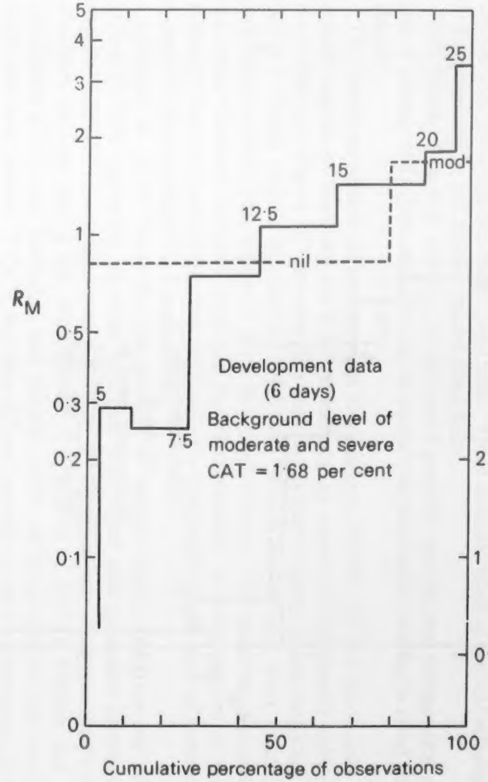

Figure 8. The relationship between the relative frequencies (R_M) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of E (empirical index) less than or equal to the values shown on the curve, within the development (6-day) data set. Pecked line is performance of CFO forecasts (complete 10-day data set).

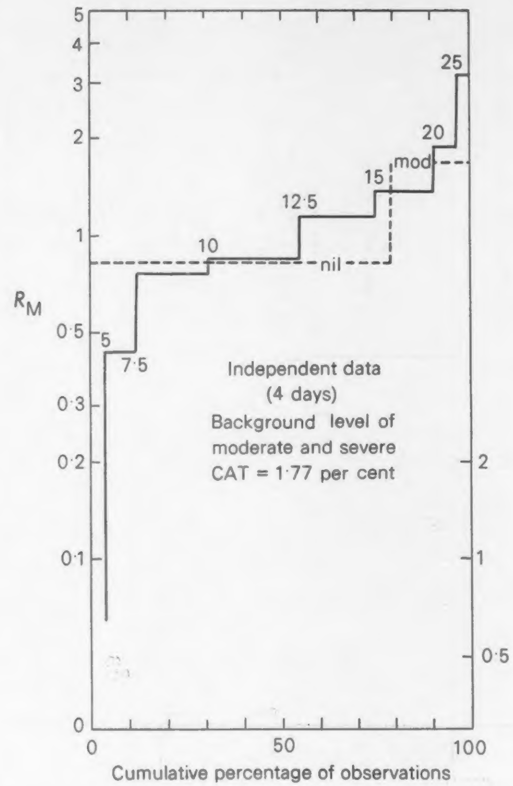

Figure 9. The relationship between the relative frequencies (R_M) of pilots' reports of CAT and the cumulative percentage of observations with forecasts of E (empirical index) less than or equal to the values shown on the curve, within the independent (4-day) data set. Pecked line is performance of CFO forecasts (complete 10-day data set).

background probability). This level of discrimination must represent a significant and useful improvement on the type of yes/no CAT forecast currently used, where as much as about 20 per cent of chart area is forecast to be particularly prone to moderate or severe CAT (with an undefined probability of encounter). The level of skill in these forecasts has been shown to be quite low: aircraft flying in regions forecast to contain moderate CAT actually experienced moderate CAT with a frequency of 1·68 times the background frequency, while those flying outside these regions experienced moderate CAT with a frequency of 0·82 times the background frequency, a difference of a factor of only two between the two forecast categories.

The fact that vertical and horizontal wind shear have emerged as easily the best of the individual meteorological indices tested is not really surprising, since our knowledge of the physical processes leading to clear-air turbulence leads us to expect a good association between CAT and vertical wind

shear; the correlation of CAT with horizontal wind shear is then implied since layers of atmosphere supporting strong vertical shear are often tilted with a typical slope of about 1 in 100, so that a component of wind shear appears in the horizontal. These characteristics of the real atmosphere appear to be well represented in the 10-level model wind fields.

The failure of vertical velocity, its horizontal gradient and the two components of the Lagrangian rate of change of (Ri) (ϕ_1 and ϕ_2) must be considered conclusive, bearing in mind the size of the 1976 sample.

The remaining indices all possess some small degree of skill, but this lies mainly in their ability to identify regions of relatively *low* CAT probability, an aspect of skill already exhibited by horizontal wind shear (see Figure 1). However, the most important property of any empirical index must be its ability to locate regions of relatively high CAT probability; vertical wind shear is clearly the best individual predictor (see Figure 2) from this point of view. The inclusion of horizontal shear in the regression equation certainly improves the discrimination between regions of relatively high and relatively low CAT probability, but improves only marginally on the skill of vertical shear in locating regions of relatively high CAT probability.

Sparks *et al.* (1977) found that the gradient of vertical velocity (∇w) was one of the most useful indices in their regression equation, and that wind speed also possessed useful predictive skill. It appears that these associations were a result of the comparatively small and biased sample of synoptic situations covered during the 1972 Survey. Sparks *et al.* (1977), Endlich and Mancuso (1965), Colquhoun (1967), and Bortnikov and Vasil'ev (1974) all found that vertical wind shear performed fairly well as a locator of CAT, but they differed notably in their experiences of the value of other indices such as vorticity, deformation, Richardson number and wind speed. These differences, again, are probably largely attributable to the fact that these surveys dealt with relatively small data sets, each made up of a very limited number of independent synoptic regimes; it is to be expected that some indices perform well in certain synoptic situations and poorly in others. In the 1976 Survey it was the intention that a wide range of synoptic situations should be included; in the opinion of the author, this objective has been achieved.

Trials of objectively derived forecasts of CAT probability, based on computed fields of horizontal and vertical wind shear, are going ahead in the Meteorological Office.

6. Concluding remarks

The results of the 1976 Turbulence Survey have shown that objective forecasts of CAT based entirely on numerical model output are potentially useful and perform better than the more conventional type of forecasts currently issued by CFO, particularly in their ability to discriminate between regions of relatively high and relatively low CAT probability. Of the eleven meteorological indices tested as CAT predictors, vertical and horizontal wind shear performed markedly better than any other index.

It is felt that probability forecasts of CAT of the type envisaged (giving grid-point probabilities of CAT per 100 km of flight) will prove more reliable and useful to airlines and pilots than those prepared using current methods. They may, for example, be particularly useful for flight-planning purposes when a choice of routes is available (e.g. across the Atlantic) since overall route probabilities of CAT can be readily calculated, given the grid-point probabilities along the route.

Acknowledgements

Thanks are due to all the national meteorological services and airlines, most particularly their pilots, who co-operated to make a success of the 1976 Turbulence Survey, and to W. R. Sparks who was

responsible for the planning, organization and implementation of the Survey. The computer programming efforts of C. Passant, S. G. Smith, K. F. Blake, Mrs M. Rowntree and Mrs P. Tonkinson were also appreciated.

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APPENDIX

Table A1. *Percentages of distance flown in clear-air turbulence—all flights*

Flight level	Reported CAT Light +	Moderate +	Severe +	Total distance flown (km)
<100	9·17	1·09*	0·242*	13 245
100–149	8·29	0·44*	0·077*	38 816
150–199	8·29	0·53	0·061*	111 895
200–249	9·19	0·67	0·018*	236 872
250–299	10·72	1·43	0·006*	686 695
300–349	8·87	0·90	0·012*	1 385 671
350–399	10·92	1·72	0·005*	1 415 676
≥400	5·30	0·24*	0·236*	16 557
All	9·92	1·26	0·013	3 905 427

Table A2. *Percentages of distance flown in clear-air turbulence—European flights*

Flight level	Reported CAT Light +	Moderate +	Severe +	Total distance flown (km)
<100	9·17	1·09*	0·242*	13 245
100–149	8·29	0·44*	0·077*	38 816
150–199	8·51	0·55	0·062*	108 970
200–249	9·31	0·70	0·019*	229 460
250–299	11·25	1·46	0·007*	644 742
300–349	9·73	0·61	—	744 909
350–399	10·82	1·25	—	317 504
≥400	6·01*	0·72*	0·717*	5 441
All	10·21	0·97	0·012	2 103 087

Table A3. *Percentages of distance flown in clear-air turbulence—Atlantic flights*

Flight level	Reported CAT Light +	Moderate +	Severe +	Total distance flown (km)
<100	—	—	—	0
100–149	—	—	—	0
150–199	—	—	—	2 925
200–249	5·48*	—	—	7 412
250–299	2·48	0·91*	—	41 953
300–349	7·88	1·22	0·027*	640 762
350–399	10·94	1·86	0·006*	1 098 172
≥400	4·96*	—	—	11 116
All	9·58	1·59	0·013*	1 802 340

* Denotes that the percentage is based on fewer than 5 encounters with CAT. Flight levels are expressed in hundreds of feet.

Table A4. *Meteorological indices computed from 10-level model fields*

1. $V = (u^2 + v^2)^{\frac{1}{2}}$
2. w computed at grid points by 10-level model
3. $|\nabla w| = \left\{\left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right\}^{\frac{1}{2}}$
4. $D = \left\{\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2\right\}^{\frac{1}{2}}$
5. $\zeta_a = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + f$
6. $S_H = \frac{1}{V^2}\left(uv\frac{\partial u}{\partial x} - u^2\frac{\partial u}{\partial y} + v^2\frac{\partial v}{\partial x} - uv\frac{\partial v}{\partial y}\right)$
7. $S_V = \frac{\partial V}{\partial p} \cdot \frac{\partial p}{\partial z}$ (empirical adjustment applied if level of maximum wind is within 30 mb of a standard level)
8. $\phi_1 = -\left(\frac{\partial \theta}{\partial p}\right)^{-1}\left(\frac{\partial \theta}{\partial x} \cdot \frac{\partial u}{\partial p} + \frac{\partial \theta}{\partial y} \cdot \frac{\partial v}{\partial p} + \frac{\partial \theta}{\partial p} \cdot \frac{\partial \omega}{\partial p}\right)$
9. $\phi_2 = -2Rf^{-1}\left|\frac{\partial V}{\partial p}\right|^{-1}(1000)^{-K}\,\mathrm{p}^{K-1} \,.\, F_p$
10. $I_D = (\nabla \,.\, V)^2 + (\zeta_a + f)^2 - D^2$
11. $Ri = \frac{1}{\rho\theta} \cdot \frac{\partial \theta}{\partial p}\left(\frac{\partial V}{\partial p}\right)^{-2}$

x,y,z orthogonal Cartesian axes of 10-level model
u,v components of horizontal wind (V) along x,y axes
w vertical velocity
ω $= (\partial p/\partial z)$
p pressure
ρ density
θ potential temperature
R gas constant
K $= R/c_p$
c_p specific heat capacity of air at constant pressure
f Coriolis parameter

$$F_p = -|\nabla\theta|^{-1}\left\{\frac{\partial \theta}{\partial x}\left(\frac{\partial \theta}{\partial x} \cdot \frac{\partial u}{\partial x} + \frac{\partial \theta}{\partial y} \cdot \frac{\partial v}{\partial x} + \frac{\partial \theta}{\partial p} \cdot \frac{\partial \omega}{\partial x}\right) + \frac{\partial \theta}{\partial y}\left(\frac{\partial \theta}{\partial x} \cdot \frac{\partial u}{\partial y} + \frac{\partial \theta}{\partial y} \cdot \frac{\partial v}{\partial y} + \frac{\partial \theta}{\partial p} \cdot \frac{\partial \omega}{\partial y}\right)\right\}$$

Vertical derivatives of variables such as u,v,w and θ were determined by fitting cubic splines to values at standard levels (at 100 mb intervals) and computing the vertical gradients *at* the standard levels.

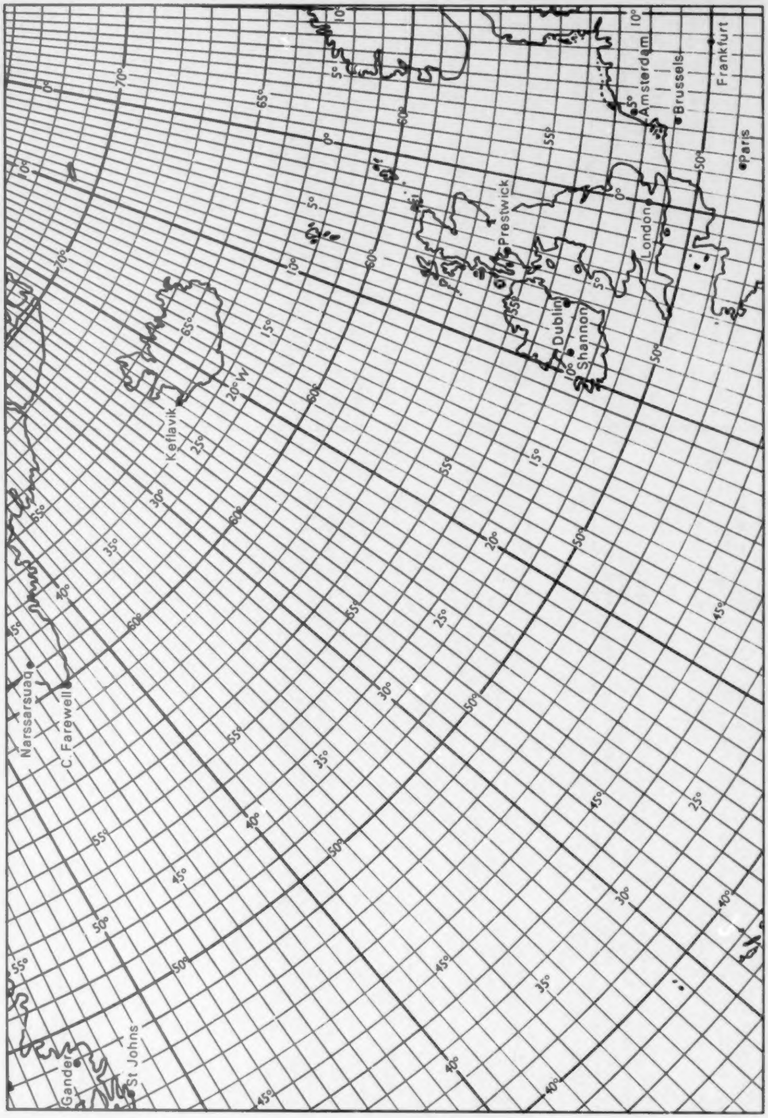


Figure A1. Turbulence Survey (1976) reporting map—ATLANTIC flights.

METEOROLOGICAL OFFICE TURBULENCE SURVEY

These maps are being issued on a few chosen days in order to help assess techniques of forecasting CAT. Captains are asked to complete the flight information section on the right and to describe the turbulence history of the cruise stage of their flight on the map overleaf. All turbulence, whether in cloud or in clear air, should be reported.

REPORTS OF NO TURBULENCE ARE AS IMPORTANT AS REPORTS OF TURBULENCE

For all points of the cruise stage within the area of the map indicate the track, flight level, and turbulence encountered. Mark the time (GMT) at convenient intervals. When LIGHT, MODERATE, or SEVERE turbulence is encountered show any cloud in the vicinity as in the example below.

Flight information

Date ....

Aircraft type ....

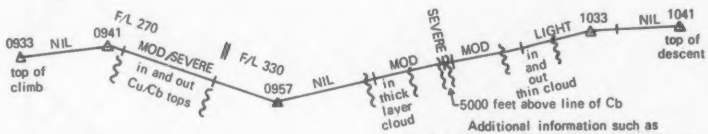
Company/Unit ....

Flight number ....

Departed .... at .... GMT

Arrived .... at .... GMT

Example



Additional information such as wind measurements would be most welcome

Key

NIL MOD Boundaries of turbulent zones

in thick layer cloud Boundaries of cloudy zones

F/L 270 || F/L 290 Changes of flight level

Time mark

(Based on ICAO Doc.8812, AN-CONF/6, 1969)

Turbulence criteria

Description	Effects
Moderate	Moderate changes in aircraft attitude and/or altitude but the aircraft remains in positive control at all times. Variations in air speed are usually small. Loose objects move about. Occupants feel strain against seat belts. Peak changes in accelerometer readings at c.g. of 0.5 g to 1.0 g.
Severe	Abrupt changes in aircraft attitude and/or altitude. Variations in airspeed are usually large. Loose objects tossed about. Occupants are forced violently against seat belts. Peak changes in accelerometer readings at c.g. of more than 1.0 g.
Light /extreme	may be reported when effects are less/greater than these.

The reasons for this survey

A CAT survey in 1972 showed that a report of CAT from another pilot within one hour was more reliable than a forecast of CAT, but when the other pilot's report was more than three hours old the forecast was better.

The objects of this survey are to improve CAT forecasts and to find ways of combining recent reports from pilots with meteorological forecasts to make CAT warnings more reliable

Captains are asked to hand maps to a British meteorological office or to their company representative at their destination to be sent to The Director-General, Meteorological Office (Met O 9), London Road, Bracknell, Berks RG12 2SZ, U.K.

Figure A2. Turbulence Survey (1976)—Reverse side of reporting map shown in Figure A1.

Review

Modification of hail processes, edited by I. I. Burtsev. 225 mm × 150 mm, pp. viii + 241, *illus*. A. A. Balkema, Publishers, Rotterdam, 1979. Price £6.50, Hfl 27.50, US $11.00.

The book is an English translation, produced in India, of a collection of Russian articles. The original papers appeared during 1973 and, except for a brief opening survey of French weather modification attempts up to 1971, were motivated by anti-hail operations in the Soviet Union during 1970–71.

The first half of the collection is made up of descriptions of various techniques. The principles and some technicalities of Doppler radar are presented, as are discussions of various properties and uses of cumulonimbus thermodynamics and multidimensional correlation techniques. The information about storm dynamics, which may be inferred from hailstone structure, is set down, although some of the assumptions necessary to put this into practice are far from convincing. In the other substantial section some assessments of the effectiveness of anti-hail operations in the Soviet Union are provided. This is an indigestible mass of information, the value of which has proved impossible to evaluate with any confidence despite attempts to make some sense of the tables and diagrams provided, with maps of the operational areas. Unfortunately the Russian concept of natural and modified hail creation processes, which one might have expected to dominate the book from its title, consists of a single qualitative article, sandwiched between these sections. The evidence for the proposed dynamics and structure of hailstorms, on which the Soviet modification process is based, is referred to but is not presented. The remainder of the book is made up of discussions of the effects of large amounts of nucleating material on the environment and, briefly, of the microwave properties of ice and water spheres.

It is difficult to find any merit in this publication. The basic material must be of intrinsic value only to a very narrow range of English-speaking interests. Furthermore, the articles are obviously not designed as reviews of their subject matter and depend heavily on Russian-language papers which are not generally available. Finally the six to seven years between first publication and translation hardly add to the value of the end product. A study of recent reports of the Swiss experiment (Grossversuch IV) and the National Hail Research Experiment in the USA is likely to provide infinitely greater insight into the realities and problems of hailstorm modification, despite the inconclusive results of these programs to date.

P. Ryder

Notes and News

50 years ago

With deep regret we learn of the disaster to H.M. Airship R 101 with the loss of 48 lives, including that of Mr M. A. Giblett, M.Sc., Superintendent of the Airship Meteorology Division. (*Meteorol Mag*, 65, Oct. 1930, p. 219).

[The *Meteorological Magazine* for November 1930 devoted 16 pages to an account of the disaster and to printing tributes to M. A. Giblett, a scientist of outstanding ability and devotion to duty whose life, in common with those of other victims, was tragically cut short. Dr (later Sir George) Simpson, Director of the Office, in the course of his own tribute to Giblett, wrote: 'The Meteorological Office has lost an assistant of whom great things were expected, an able scientist, and an exceptional organiser'.]

Mr J. S. Dines

Mr John Somers Dines, the last of a distinguished family of meteorologists, died on 15 May 1980 in his 95th year. His grandfather, Georges Dines (1812–87), invented the dew-point hygrometer; his father, W. H. Dines, F.R.S. (1855–1927), was the inventor of the pressure-tube anemometer and the tilting-siphon rain-recorder and pioneered the exploration of the upper air; his brother, L. H. G. Dines (1883–1965), was for many years Superintendent of Kew Observatory.

J. S. Dines was educated at Emmanuel College, Cambridge and graduated in mathematics in 1906 by which time he had already been assisting his father and brother in their meteorological researches; W. H. Dines was an engineer by profession, and his son gained much invaluable experience of engineering and instrument making by working with him.

J. S. Dines first entered the Office in 1907 as a Student Assistant. In 1910 he was appointed as Meteorologist in charge of experiments for the Advisory Committee for Aeronautics and in 1911 went as Meteorologist to the Branch Office at South Farnborough. In 1915 he joined the Forecast Division and in 1920 was promoted to become Superintendent. In 1929 he was appointed Superintendent of Instruments and of Army Services and he held this position until he retired from the Office in 1939. He published a number of scientific papers during his career and was responsible for writing the second edition of the *Weather Map*, the first edition of which had been written by Sir Napier Shaw; he also investigated the meteorological factors responsible for the very serious flooding of the Thames in London in January 1928, work which led ultimately to the setting up of the Storm Tide Warning Service in 1953.

After his retirement he lived quietly at his home in Hermitage, near Newbury, taking, however, an active interest in local government and church affairs. He retained an interest in meteorology and other scientific pursuits until the end of his life, and letters from him would appear from time to time in *Weather* or the *Quarterly Journal of the Royal Meteorological Society*.

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NOTICES

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